Pramāṇa, Vol. 19, No. 4, October 1982, pp. 323–336. © Printed in India.

Two million volt terminal tandem accelerator

M G BETIGERI, T P DAVID, S C HIREMATH*, P K IYENGAR, M K MEHTA, V S RAJU†, P SINGH and J N SONI
Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay 400 085, India
*Heavy Water Project, Kota, Rajasthan, India
†Analytical Chemistry Division, BARC, Bombay 400 085.

MS received 10 April 1982; revised 3 July 1982

Abstract. Design and construction details of a horizontal 2 MV Tandem Van de Graaff accelerator built at Bhabha Atomic Research Centre are given. A terminal voltage of 2·15 MV has been achieved. Energy analysed Corona stabilized beams of protons and oxygen ions have been obtained. Experiments have been carried out to test the performance of the accelerator.

Keywords. Tandem accelerator; energy stabilized proton; oxygen beams.

1. Introduction

In the last decade, a low energy tandem accelerator has become an important component in a set-up to study atomic spectroscopy. This has come about mainly following the recent advances in the negative ion source technology (Tykesson 1978, Brand 1977), whereby ion species of almost all elements can be accelerated. However, many of the accelerators are equipped with beam handling components inadequate to handle heavy ions of interest in the study of atomic spectroscopy. A new generation of low energy tandem accelerators equipped with sputter ion sources and beam handling capability for the heavy ions are being currently built. Possibility of using tandem accelerator as a sensitive mass separator for an accurate estimate of low concentration of isotopes (parts per billion level) has opened up vast potentialities in the field of geochronology (Gove 1978, 1980). The versatality of such a low energy accelerator in other basic and applied fields including industrial applications has been well established (Duggan and Morgan 1980).

In the present paper, design and construction details of a 2 MV Tandem Van de Graaff accelerator entirely built at Trombay is described. A new electrode geometry for the accelerating tube has been tried and has shown satisfactory ion optical properties (Singh 1982). All the beam handling elements have been designed to handle heavy ions. Proton and oxygen ion beams are at present routinely available. A block diagram of various components of the accelerator is shown in figure 1. Detailed description of the facility namely the voltage generator, the beam handling components including the ion source and the terminal voltage stabilization is given in the following three sections. The performance of the accelerator is discussed in § 5.

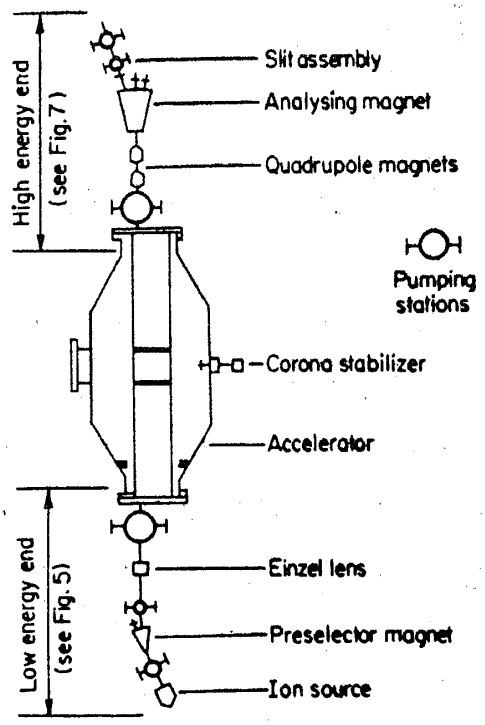

Figure 1. Block diagram of 2 MV Tandem accelerator.

2. Voltage generator

The voltage generator consists of a charge sprayer and an insulating belt conveyor which charges the insulated terminal supported by two column structures on either side mounted on the two end cover flanges of a pressure vessel in cantilever arrangement (figure 2). An electrostatic potential upto 2·15 MV has been achieved. The term column structure refers to the region where an uniform field gradient is established by means of conducting planes properly insulated from each other and a resistance chain. In the present set-up, two support columns each consisting of 49 sections are assembled—each section being separated by nine unglazed ceramic insulators of 25 mm thickness. A column plate (3 mm thick 2S aluminium plate, 575 mm in diameter) assembly (figure 3) consists of gradient bars to provide smooth surface to the belt, spark gaps and smooth polished hoops made of aluminium tubing (12 mm OD, 6 mm ID). Each of these column sections define an equipotential plane of 40 kV/section. The column plates are bonded together (figure 4) using commercially available two-component adhesive. The voltage generator is placed inside a pressure vessel (I.D.=1·97 m, length=4·72 m, thickness 25 mm) so that high gas pressure provides the necessary insulation to sustain high voltage gradients. The maximum radial voltage gradient for 2 MV on terminal for the present geometry is 90·8 kV/cm. This includes the corrections due to irregularity in the shape of the inner cylinder due to the presence of hoops. The axial voltage gradient between two neighbouring column sections for the present geometry (gap g=25 mm, diameter of the hoop d=12·5 mm g/d=2) has been calculated to be 41·6 kV/cm. Since the spark gaps placed between two column sections result in a gap of 3 mm, the insulating gas pressure must be maintained at 11 kg/cm^2 to maintain such gradient assuming a 30 kV/cm gradient at one atmosphere gas pressure. A pressure vessel to withstand an internal gas pressure

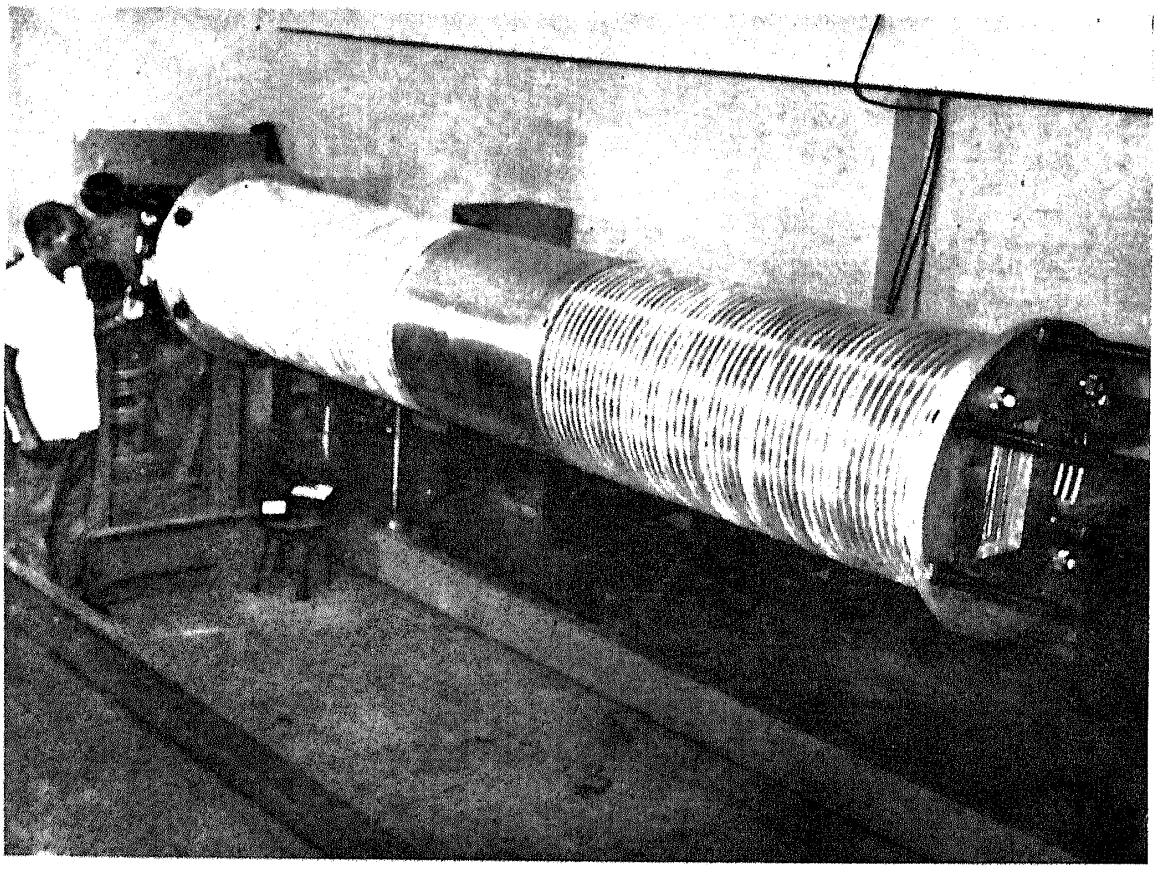

Figure 2. Voltage generator assembly showing the two-column structures in cantilever arrangement.

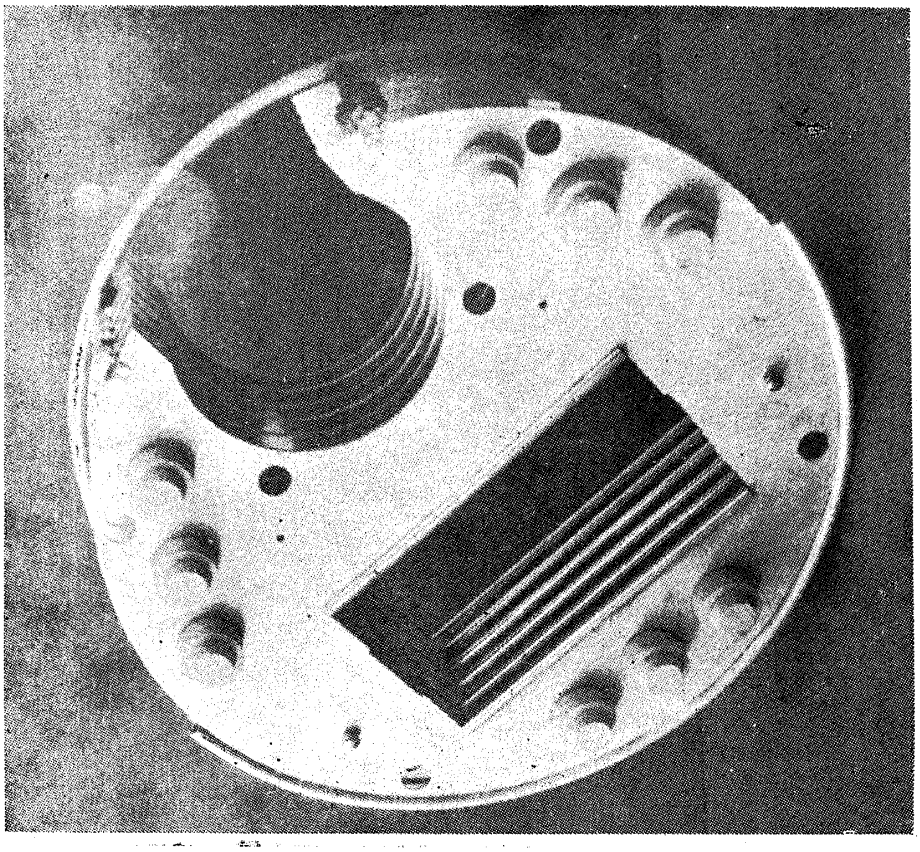

Figure 3. Configuration of a column plate.

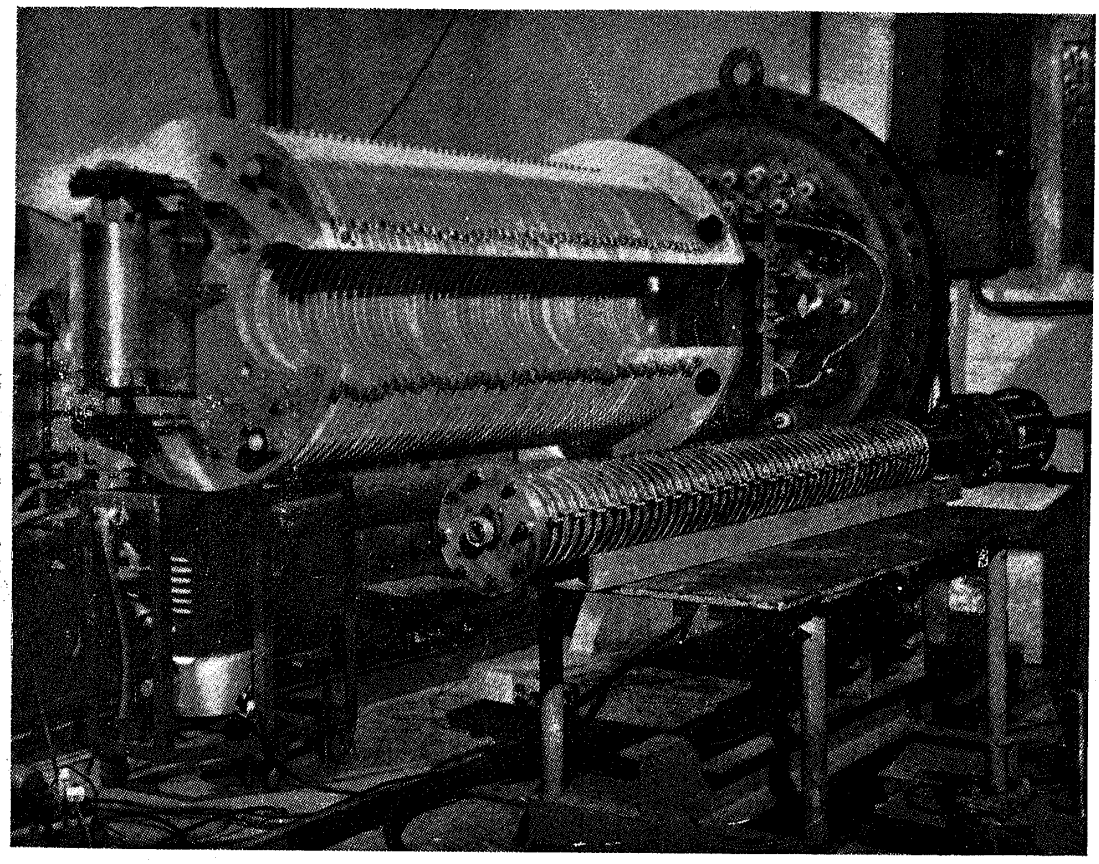

Figure 4. Column structure details and the accelerating tube.

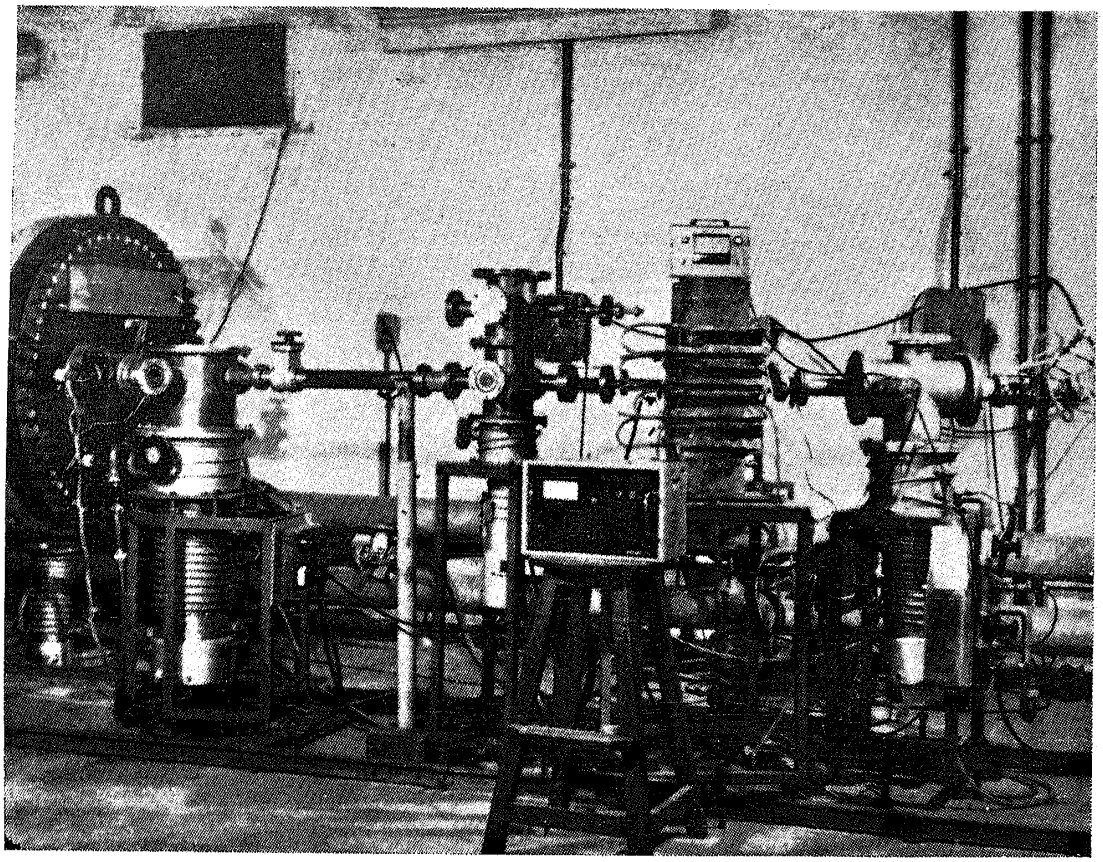

Figure 5. Beam handling components—low energy end. (For legends see Figure 1)

of 17·6 kg/cm^2 has been designed and fabricated to ASME specifications. A dry mixture of nitrogen and carbon dioxide has been used in the present set-up though dry SF_6 may allow a higher voltage to be attained.

A nylon endless belt (220 mm wide, 1·2 mm thick) running between the terminal pulley and a specially designed 1·5 HP 'inverted' motor conveys electric charge to the high voltage terminal. The mount supporting the pulley in the terminal is adjustable to provide the necessary belt tension. A variable belt charge power supply (0-30 kV 8 mA DC) is connected to a charging screen kept slightly rubbing on to the belt through a constant current device which acts as a variable series impedance in the belt charge circuit.

A current drain of 10 μA from one column plate to the next through 4000 MΩ resistors results in potential steps of 40 kV per section uniformly from high voltage terminal to the ground when the accelerator operates at 2 MV. A chain of sixteen resistors (250 MΩ each) is mounted in a high density polystyrene box with spring-loaded end terminals. This is fitted at the centre of the belt space, diagonally between two adjacent column plates. The resistors at the ground ends of the two column sections are connected to ground through current meters to monitor column currents —thus providing a rough terminal voltage measurement.

3. Beam handling

In a tandem configuration, the high voltage V achieved at the terminal is used first for accelerating singly-charged negative ions to energy eV and then further accelerate the positive ions produced in a charge exchange canal in the terminal to energies n eV where n is the charge state of the positive ion produced in the stripper. The beam handling components are, therefore, divided into three groups with one group at the low energy end of the accelerator and the other group at the high energy end of the accelerator in addition to a third group consisting of accelerating tubes and the stripper canal located inside the pressure vessel. The beam handling components, at the low energy end (figure 5) consist of a negative ion source, and ion optical elements consisting of Einzel lenses and 20° preselector magnet for mass selection. The ion source used is a modified version of a duoplasmatron earlier developed in this laboratory (Betigeri *et al* 1975). A cross-sectional view of the ion source is given in figure 6. Negative ions are directly extracted from the ion source by displacing the intermediate electrode axis by 1·5 mm with respect to the beam axis. Optimized values for the ion source parameters are listed in Appendix. Two Einzel lenses are used for focussing low energy negative ion beam—one before injecting into the magnet and the other one after the magnet but before injecting into the accelerating tube. The 20° preselector magnet has been designed to analyse 100 keV singly-charged ions of $A=240$ amu. The K value ($= ME/Q^2$) for the magnet is 24. The current in the magnet coils is stabilized to 0·1%. Typically, extracted negative ion beams listed in Appendix are measured in a Faraday cup after the magnet. The second Einzel lens enables selection of suitable input characteristics to match the ion optical requirements of the accelerating tube.

The accelerating tube (figure 4) consists of a periodic repetition of an 'index' glass ring (127 mm OD, 82 mm ID, and 25 mm thick) and specially-shaped stainless steel electrode (140 mm OD, 50 mm ID and 0·8 mm thick). There are 50 sections in each

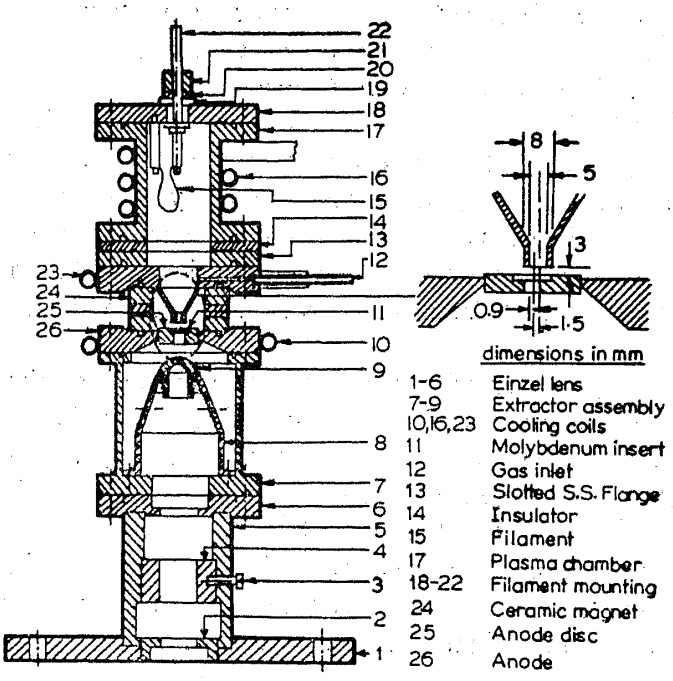

Figure 6. Cross section of direct extraction negative ion source.

tube. The accelerating tubes are mounted on the pressure vessel flanges through bellows to facilitate alignment. Each of the electrode is electrically connected to a corresponding column plate. Hence the charged particles travelling in vacuum inside the tube gain 40 keV energy per unit charge per section corresponding to a terminal voltage of 2 MV. The focussing properties of this accelerating tube have been studied and are reported in Singh (1982). The ion optical calculations for the accelerating tube suggest the necessity of grading the accelerating voltages in the first few sections of the accelerating tube. Based on these calculations, we have adjusted the values of resistors in the first few sections so that the particle gains an energy of 10 keV in the first two sections, 20 keV in the 3rd section and later a constant acceleration of 40 keV per section. The stripper canal is a 6 mm I.D. stainless steel tube of lengt h610 mm connected between the two terminal ends of the accelerating tubes. Oxygen gas at a pressure of 10 μ (corresponding to $N=10^{16}$ atoms/cm^2) is optimum for a charge exchange process. This is true assuming that the cross-section for charge exchange (σ) is of the order of 10^{-16} cm^2 so that $N\sigma\approx 1$. The positive ion produced at the terminal are further accelerated in the 2nd accelerating tube.

The third group of beam handling components (figure 7) includes quadrupole lenses and analysing magnet. The quadrupole lenses focus the beam coming from the accelerator which is slightly diverging. As a result of the charge exchange process in the stripper canal, the exit beam is composed of various charge states and hence of different energies. The analysing magnet, together with settings on quadrupole lenses therefore selects out a particular charge state. The analysing magnet (K=160) bends the beam through 20° and has a bending radius $\rho=141{\cdot}7$ cm. It uses hollow aluminium conductor for its coils and the current is stabilized to better than 30 ppm. The field is measured using a NMR digital gaussmeter.

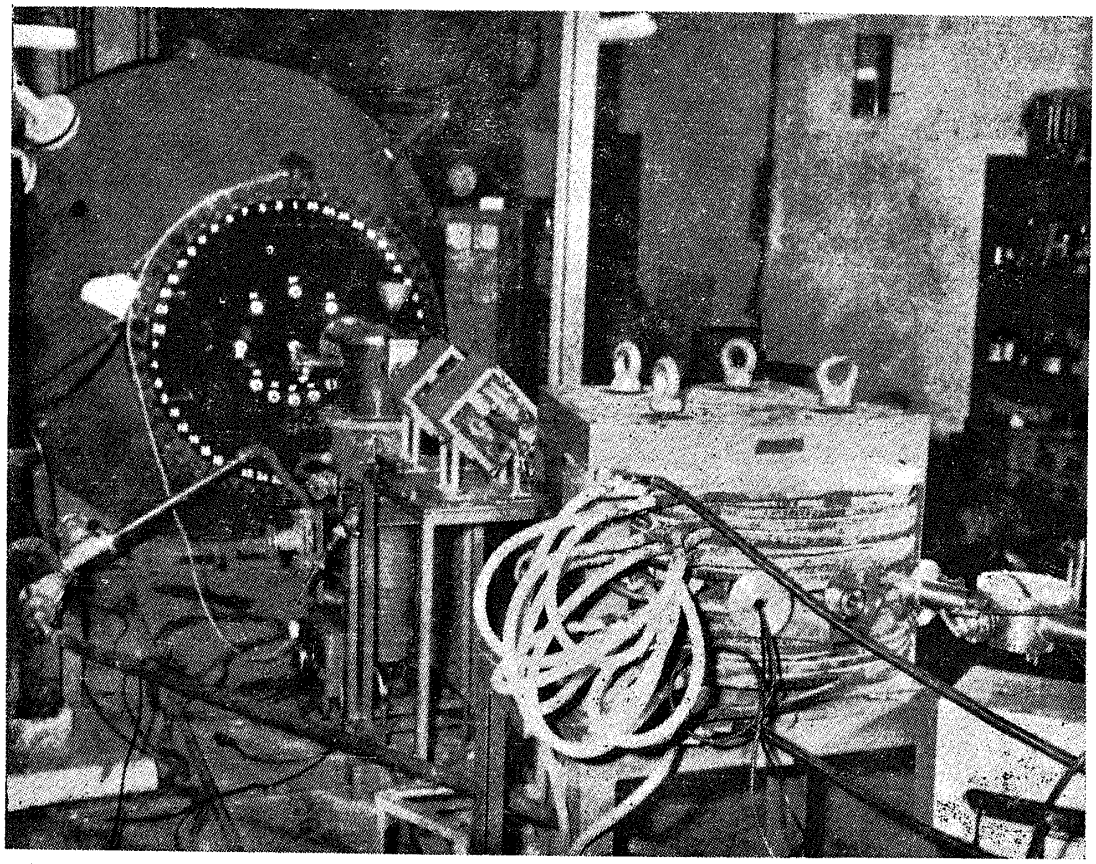

Figure 7. Beam handling components—high energy end. (for legends see figure 1).

4. Terminal voltage stabilization

For any meaningful experiments to be performed with an accelerator, it is necessary that the energy of the incoming beam of charged particles be accurately known and controllable. In electrostatic accelerators this requirement amounts to demanding a stable terminal voltage and to be able to vary. This is achieved by installing a corona feedback control system. The corona collector assembly consisting of a group of fine needles projected at a short distance with respect to the high voltage terminal is mounted on the tank flange located centrally along the axis of the tank facing the terminal. The shaft carrying the corona collector needles is driven by a remotely controlled reversible motor. This motor also drives through a suitable reduction gear a 10-turn potentiometer which is connected to a 1.5 V battery through a micro-ammeter on the control panel and is calibrated to indicate the position of the corona collector needles inside the pressure vessel. The corona current is drawn through the plate of a power tube (4D21) which is controlled by its biasing derived from the feed back system (figure 8).

The feedback is obtained from signals picked up on a pair of insulated slits which are located in a chamber after the 20° analysing magnet. Depending on the variations in the analysed energy of the particles, the slits which are separated by 1 mm from each other pick up the beam corresponding to larger or smaller radius of curvature. The charge picked up on these slits is separately amplified by a low noise high sensitivity operational amplifier (LM 308). The amplified signals are connected to a balance amplifier. When the two slits receive the same current, the balance amplifier gives no output. Off-balance curent is further amplified and serves to bias the grid with respect to the cathode of a 4D21 tube which in turn controls the plate current. The overall gain of the balance amplifier system is such that with a minimum current of to 4 nA on the slits, the feedback system operates satisfactorily to give a stable proton beam.

5. Performance

The pressure vessel is pressurized to 15 kg/cm^2 with a gas mixture of carbon dioxide and nitrogen in the ratio of 1:4. The accelerating tubes are evacuated using two 2000 l/sec oil diffusion pumps on either side. The beam lines are evacuated by two 500 l/sec oil diffusion pumps. All the four pumps are backed by a 800 l/see vapour booster pump which provides an ultimate backing pressure of 10^{-4} torr with a rotary backing pressure as high as 1 torr. A 150 l/min rotary pump is used to back the booster pump. On each diffusion pump, there are specially designed online liquid nitrogen traps—to avoid backstreaming oil vapour condensation on the accelerating tubes. In a typical run, it is relatively easy to obtain 2×10^{-6} torr in the entire system within one hour from the start-up.

In a continuous run of 4 weeks, voltage testing with the accelerating tube in position was performed. A terminal voltage upto 2·15 MV has been realized. During the run, the dew point of the gas mixture was measured to be −40°C. For the beam trial, 20 keV H^-ions were injected into the accelerating tube. The beam monitoring is done at various places along the beam line. Initially, a stabilized beam was obtained at 500 kV terminal voltage. The insulated control slits, from which error signals

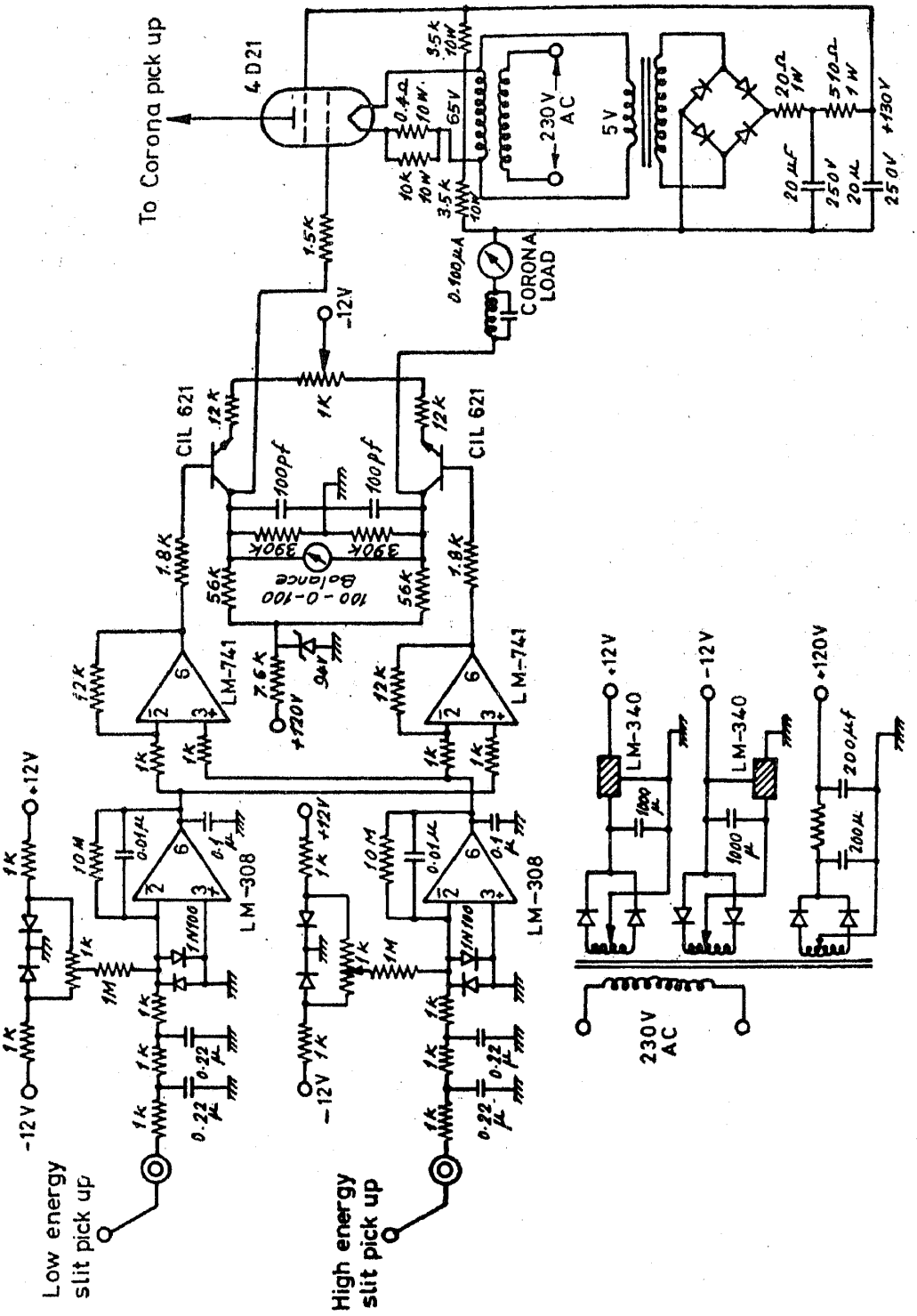

Figure 8. Circuit-diagram-terminal voltage stabilization.

CORONA STABILISATION CIRCUIT FOR 2MV TANDEM

were obtained for corona stabilization, were adjusted to be 1 mm apart. The beam intensity obtained after the energy analysis in Faraday cup located behind the slits was 175 nA. The beam transmission is not satisfactory at low terminal voltages. The transmission can be improved for protons if the present gas stripping is replaced by foil stripping.

A calibration experiment to measure (p, γ) resonances on ^{27}Al has been done. The resonances chosen are those corresponding to incoming proton energies of 992 keV and a doublet at 1381 and 1388 keV. The widths and strengths for these resonances have been recently measured (Meyer *et al* 1975). An evaporated (100 μg/cm^2 thick) Al target on Ta backing was kept in the Faraday cup. Using a 3″ × 3″ NaI(Tl) scintillation counter, an excitation function for the reaction $^{27}Al(p, \gamma)^{28}Si$ between proton energies corresponding to 500–700 kV on the terminal in steps of 5 keV has been measured (figure 9). The charge collected on the Faraday cup (with an electron suppressor) is used for normalizing the yield at different energies. The FWHM corresponds to 24 keV. Since these resonances have very small widths, widths of the resonances in figure 9 correspond to the effects due to target thickness and spread in the beam energy. The contribution to the width due to target thickness is estimated to be 20 keV. The spread in beam energy ($\triangle E$) therefore is deduced as 13 keV. It would be possible to reduce $\triangle E$ by relocating the control slits at the appropriate crossover point farther down the beam line away from the magnet. This optimization has not yet been done.

With the present ion source, it is possible to extract beams of negative ions of gases. Using in the source a gas mixture of argon and oxygen, O^- beam up to 2 μA has been obtained at 20 kV extraction voltage. The negative oxygen ions have been accelerated at a terminal voltage of 800 kV. Charge states corresponding to 3^+, 2^+, 1^+ could be identified with analysed beam currents of 18 nA, 30 nA and 3 nA respectively The loss of transmission could be due to variety of reasons. The negative ion extraction energy is low. Significant beam loss could possibly take place even before it enters the accelerating tube. The accelerated beam contains various charge states. The quadrupole focussing for a particular charge state always results in bad focussing for others. In spite of all this, the charge distribution measured is close to that expected at this velocity.

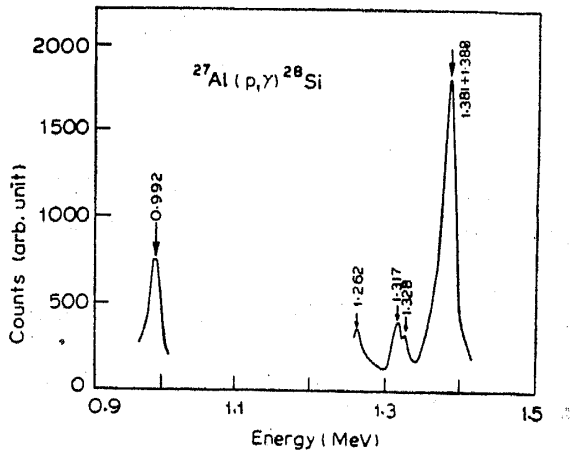

Figure 9. Excitation function for $^{27}Al(p, \gamma)^{28}Si$ reaction.

6. Conclusions

A 2 MV tandem Van de Graaff accelerator has been indigenously built and satisfies all the design criteria. An energy-stabilized proton beam has been obtained. The beam transmission would be improved in course of time. With improvement in the humidity of the gas and conditioning of the machine, better performance at higher voltage can be achieved. A versatile sputter ion source for negative ions has been fabricated which is yet to undergo detailed tests. This ion source, when installed, will extend the utility of the accelerator considerably.

Acknowledgements

We thank Shri Challappa and his colleagues of the Central Workshops, BARC for fabricating the pressure vessel and the analysing magnets. The intiative taken by the Electrical Works Section, BARC in designing and fabricating the 'inverted' motor is appreciated. We thank the Reactor Control Division, BARC for pressing the stainless steel electrodes to the required shape. We thank Dr C V K Baba, Shri P J Bhalerao and Shri M Y Vaze for discussions at various stages and help in designing quadrupole power supplies and the balance amplifier used in the terminal voltage stabilization system.

Appendix. Optimized ion source parameters

1. Distance between intermediate electrode and anode		= 3 mm
2. Aperture in the anode		= 0·9 mm
3. Gas pressure		= 0·1 Torr
4. Distance between anode and extractor		= 3 mm
5. First discharge current		= 300 mA
6. Second discharge current		= 800 mA
7. Extraction voltage		= 20 kV
8. Einzel lens voltage		= 11 kV
9. Extracted current	H^-	= 10 μA
	O^- (A=16)	= 2 μA

References

Betigeri M G, Bhatia M S and David T P 1975 *Nucl. Instrum. Meth.* **128** 29

Betigeri M G, David T P, Iyengar P K, Mehta M K, Raju V S, Singh P and Soni J N 1982 BARC Report—under preparation

Brand K 1977 *Rev. Phys. Appl.* **12** 1453

Duggan J L and Morgan I L (eds.) 1980 6th Conf. Proc. on *Application of accelerators in research and industry*, Denton, Texas (and earlier conferences)

Gove H E (ed.) 1978 Conf. Proc. *Radiocarbon dating with Accelerators*, Rochester

Gove H E 1980 *Comm. Nucl. Particle Phys.* **9** 113

Meyer M A, Venter I and Reitmann D 1975 *Nucl. Phys.* **A250** 235

Singh P, David T P and Betigeri M G 1982 *Pramana* **19** 337

Tykesson P 1978 Symposium of North-eastern Accelerator Personnel, Oak Ridge, Tennessee, USA